Dynamical Control of Rapid Tropical Cyclone
Intensification by Environmental Shears

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LONG-TERM GOALS

The long-term goal of this project is to advance our understanding of the fundamental mechanisms of formation and explosive intensification of tropical cyclones (TCs). Of particular interests are the roles and interactions of the environmental shears and TC internal dynamical processes in changing TC intensity.

SCIENTIFIC OBJECTIVES

Improve our understanding of the physical processes by which (a) 3-D environmental shears, in particular the low-level meridional shear and upper-level vertical shear affect inner core structure and intensity, and (b) the mesoscale vortices, outer spiral rainbands, inner spiral rainbands, and the eyewall interact and affect TC development and intensity change.

General questions to be addressed include: (a) How is the asymmetric structure generated in association with the environmental forcing? (b) How does the change of the structure affect TC intensity? (c) What are favorable environmental conditions for the tropical cyclone formation and rapid intensification in the western North Pacific? (d) How do changes in the environment control the movement and formation in the western North Pacific region?

APPROACH

Our approach is to combine observational analysis, numerical modeling, and diagnostic analysis of the physical mechanisms. This strategy include

1.   Analyzing observed data to identify environmental controls and internal structure changes in the (a) rapid development of tropical depressions into a tropical storm (TS formation), and (b) explosive intensification of tropical storms;

2.   Designing and performing numerical experiments with a realistic hurricane model (TCM3) to reveal major processes by which the environmental forcing affects the structure and intensity.

3.   Developing diagnostic tools for studying energetics, potential vorticity, angular momentum, and heat and moisture budgets. The budget diagnostics will help elucidate internal dynamic processes in the core region that could alter the thermodynamic efficiency of the TC intensification.

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4. Conduct real case and climate simulation of the TC track and intensity using MM5 and focusing on the western North Pacific region.

WORK COMPLETED

This project has involved an integrated effort of a group of people (PI, Co-PIs and graduate students, Justin Vemtham, Kevin Mullen, Bo Yang, Bing Fu, and Tom Dunn). Major works that have completed or have a draft manuscript in preparation for publication are summarized here.

A.   Composite analysis of the environmental conditions favorable for rapid intensification of TC over the western North Pacific;

B.   Pre-hurricane radial structure of tangential velocity and vorticity obtained from aircraft observations;

C.   Why the asymmetry is destructive to the intensity of mature tropical cyclones;

D.   A parameterization for sea surface roughness in high wind regimes based on recent GPS dropsonde data and its effect on tropical cyclone intensity;

E.   Current understanding of tropical cyclone structure and intensity changes–A review ;

F.   F. How strong vertical shear a mature tropical cyclone can resist?

G.   Cyclogenesis in the western North Pacific as revealed from satellite data

H.   Simulation of cyclogenesis associated with TC Rossby wave energy dispersion

I.   Eyewall contraction, breakdown and reformation in a landfalling Typhoon Zeb

J.   Assessing the impacts of global warming on tropical cyclone tracks;

K.   Effects of air-sea interaction on TC motion

RESULTS

A. Composite analysis of the environmental conditions favorable for rapid intensification of TC over the western North Pacific

Justin Ventham has identified the major flow patterns that occur around western North Pacific tropical storms that intensify rapidly (30kts/24hrs) by composite analysis and EOF analysis. It is found that the most rapidly intensifying cases (>40kts/24hrs) are almost always associated with the monsoon confluence patterns (90%). A common mode of trough interaction from a PV perspective that occurs prior to rapid intensification was identified. 20% of cases of rapid intensification involve a clear trough interaction. The mode of interaction looks very similar to that discussed in the Atlantic study of Hanley at al. (2001) where at upper level PV anomaly approaches but does not cross the lower level TC center resulting in the destruction of the PV anomaly and then rapid intensification of the TC. This result is significant in that it shows that the physical mechanisms elucidated in the ECMWF data in the Atlantic also appear to occur in NCEP/NCAR data in the WNP. This gives more confidence that this type of trough interaction is not just a facet of Atlantic based ECMWF data.

B. Pre-hurricane radial structure of tangential velocity and vorticity obtained from aircraft observations

We revisit the problem of basic structure of tropical cyclone (TC) vortices, emphasizing the swirling circulation and pre-hurricane stage of storm lifecycle. This work is motivated in part by recent theoretical studies, based on vortex Rossby wave dynamics, concerning the resiliency of precessing idealized vortices to environmental vertical wind shear. The radial gradient of potential vorticity, $\gamma\ (\equiv dq/dr)$, at a critical radius located between roughly 2-3 Radius of Maximum Winds (RMW) determines the stable (re-alignment, $\gamma < 0$), unstable (shears apart, $\gamma > 0$) or neutral ($\gamma = 0$) tilted-

vortex response. The question is raised regarding how realistic are the idealized profiles commonly used in theoretical studies of the evolution of pre-hurricane TCs.

Radial profiles of flight-level tangential wind observations of pre-hurricane Atlantic and eastern Pacific storms are utilized to estimate profiles of relative vorticity, which serve as a proxy for PV, in order to make comparisons with four idealized vortex profiles from the Rankine, Rankine-with-skirt (RWS), Gaussian and Smith (1990) analytic formulations. From the storm center to roughly twice the maximum wind radius, most observed vortex profiles exhibit characteristics between the RWS and Gaussian idealizations. The "skirt" of appreciably non-negative relative vorticity observed in all cases just outside the RMW confirms that *the tangential wind never decays as fast as a pure Rankine vortex*. Beyond 2 RMWs, in the critical region, the tangential wind most often decays more slowly than all idealizations and never decays faster than a RWS vortex, consistent with the appreciably non-zero relative vorticity observed. The results suggest that *real* tropical storms are able to survive episodes of vertical shear. Use of unrealistic vortex profiles in past theoretical studies of TC evolution may have produced unrealistic results.

C. Why the asymmetry is destructive to the intensity of mature tropical cyclones

Bo Yang and Yuqing Wang have investigated the effect of inner core asymmetries on TC intensity through a comparative study of a three-dimensional Tropical cyclone model (TCM3) and its simplified axisymmetric version. Both the 3-D and axisymmetric models have identical model vertical resolution and initial conditions and use the same set of parameters. The model results show that the presence of asymmetric component in the 3-D experiment reduces the final TC intensity in its mature stage. A new hypothesis is proposed to explain the destructive effect of the asymmetric structure on TC intensity. A critical factor is the efficiency in achieving entropy deficit at the ocean surface beneath the eyewall. In the symmetric TC, an annular tower of high PV is formed due to the convective heating in the eyewall. The tilting of the eyewall is consistent with the theory of slantwise neutral convection. Evaporation cooling and associated downdraft under the tilted eyewall tend to dry up the sub-cloud layer, which favors for achieving large entropy deficit at the ocean surface beneath the eyewall. For the 3-D TC, the reverse of the radial PV gradient within the eyewall region induces dynamics instability, causing PV rearrangement. The PV rearrangement is most significant at the upper troposphere due to low inertial stability, resulting in a less tilted eyewall, which is unfavorable for the formation of downdraft underneath. Also the boundary layer relative humidity increases gradually as the low-level air parcel flows inward. Thus the entropy deficit at the surface underneath the eyewall decreases and the final intensity is reduced.

D. A parameterization for sea surface roughness in high wind regimes based on recent GPS dropsonde data and its effect on tropical cyclone intensity

Yuqing Wang has constructed a parameterization scheme for sea surface momentum roughness length, applicable for all wind regimes including high winds under tropical cyclone conditions based on the latest measurements from Global Positioning System (GPS) dropsonde. The sea surface roughness length used in most existing numerical weather or climate models is generally based on the Charnock relation, which was validated only for wind speeds up to 25 m s^{-1}. Any application to higher winds, such as in the model used for TCs, is an extrapolation, which predicts a monotonic increase of drag coefficient with the increase of wind speed. Latest observational and theoretical studies, however, show that this trend will break down at some high wind speed beyond which the drag coefficient decreases with increasing wind speed. The new scheme reproduces an increase of the drag coefficient with the increase of wind speed up to 40 m s^{-1} and then a decrease with the increase of wind speed as shown by Powell et al. (2003) from the analysis of GPS observations in tropical cyclones. The effect of

the proposed parameterization on TC intensity is evaluated using the axisymmetric version of TCM3 (Wang 2001, 2002). The results show that the final maximum intensity of the simulated TC is increased by 25% in the maximum surface wind with the new scheme compared to the traditional parameterization. This increased intensity results mainly from the reduction of frictional dissipation at the sea surface under the eyewall of the storm since the increase in enthalpy flux is too small to explain the increased storm intensity (Wang 2003).

E. Current understanding of tropical cyclone structure and intensity changes–A review (Wang, Y., and C.-C. Wu)

A fundamental frequently asked question is how a TC-like vortex can sustain a coherent vertical structure in vertical shear. Wang and Holland (1996c) found in a numerical study that the cyclonic portion of the TC could remain upright in a moderate vertical shear. The TC core underwent successive downshear tilting during the first 24-h while realigning over a 72-h period. A quasi-steady tilt to the downshear left was found even in the case where the diabatic heating was not considered. They explained this steady-state tilt configuration as a result of complex interactions among the upper-level anticyclonic PV anomalies, the cyclonic portion of the vortex and the external vertical shear. Wu and Wang (2001b) found that the asymmetric diabatic heating due to vertical shear tends to offset the vertical tilt through a fast adjustment between the asymmetric flow and asymmetric diabatic heating. To understand the vertical alignment of a titled TC-like vortex, Reasor and Montgomery (2001) developed a new theory, which separates the mean vortex evolution from the evolution of the tilt asymmetry. From this new perspective, the vertically averaged azimuthal mean component of a tilted vortex is defined as the mean, while the departure from this mean as the tilt perturbation. The subsequent evolution of the tilt perturbation was captured by a linear, dry VRW mechanism. They found that the continuum modes in the dynamical system destructively interact with the VRW, leading the decay of the VRW and hence the vortex tilt. Schecter et al. (2002) viewed the vertical alignment as a result of the damping of the VRW due to its interaction with the mean vortex circulation. Reasor et al. (2003) further show that the VRW damping mechanism provides a direct means of eradicating the tilt of intense TC-like vortices in unidirectional vertical shear, and that intense TC-like vortices are much more resilient to vertical shear than previously believed. Therefore, the VRW damping mechanism intrinsic to the dry adiabatic dynamics of the TC vortex may play a crucial role in maintaining the vertically coherent structure of TCs in moderate vertical shear. In collaboration with Mike Montgomery, the linear prediction of Reasor et al. (2003) was validated using our TCM3. It is found that the linear prediction can capture the major features of the vertical alignment processes. However, the modification of the mean vortex by the wave-mean flow interaction should be taken into account to interpret the behavior of the vortex in vertical shear in a full physics model. In particular the diabatic heating contributes to maintain the strong vortex and a structure more favoring the vertical alignment.

F. How strong vertical shear a mature tropical cyclone can resist? (Wang, Y., B. Wang, and M.T. Montgomery, in preparation).

It has been shown in earlier observational studies (e.g. Gray 1968; Merrill, 1988) that the vertical shear of horizontal wind has a negative influence on the intensification of TCs. A common explanation of the effect of vertical wind shear is that the heat of condensation released at upper levels is advected in a different direction relative to the low-level cyclonic circulation and therefore the "ventilation" of heat away from the circulation inhibits the development of the storm (Gray, 1968). The vertical shear-induced convective asymmetry in the inner core region is also considered to be negative to TC intensification (Elsberry et al. 1992). Wang and Holland (1996c) and Bender (1997) attributed the

development of convective asymmetries in the inner core region of a TC embedded in a vertically sheared environmental flow to the relative flow across the elevated cyclonic relative vorticity core. They showed that both upward motion and convection were enhanced to the downshear left of the TC center but suppressed to the upshear right when facing down shear. This distribution of asymmetry in eyewall convection due to vertical shear has also been found later by Frank and Ritchie (1999, 2001) using more sophisticated high-resolution model and by Corbosiero and Molinari (2002, 2003) and Black et al. (2002) from observations. Frank and Ritchie (2001) attributed the weakening of the TC in their simulation to the outward mixing of high values of PV and equivalent potential temperature by the vertical shear-induced asymmetry in the upper troposphere, resulting in a loss of the warm core at upper levels and weakening of the storm. This mechanism does not need evident vertical tilt of the TC as it was found in a low shear of 5 m s^{-1} in which a mature TC weakened after 3 days. Since observations show that TC can sustain much larger vertical shear (Zehr 1992), it is suspected that Frank and Ritchie's simulations might be affected by the lateral boundaries of the fixed finest mesh configuration since when the TC moved toward the lateral boundary outer rainbands might be generated ahead of the storm center due to the mesh-interface discontinuity. With the latest version of TCM3, our numerical experiments show that a strong mature TC can resist the vertical shear as strong as 15 m s^{-1} due to the vertical alignment mechanism (Wang et al. 2003).

G. Cyclogenesis in the western North Pacific as revealed from satellite data
The tropical cyclone (TC) formation has long been a challenge problem owing to the lack of reliable observations over the oceans. The modern satellite products provide a unique opportunity to detect this important meteorological phenomenon. Using the QuikSCAT surface wind and the Tropical Rainfall Measurement Mission (TRMM) Microwave Image (TMI) precipitation data, the authors identified various cyclogenesis processes in the western North Pacific during the 2000-2001 typhoon seasons. Among them are the Rossby wave energy dispersion of a pre-existing TC, the energy accumulation of easterly waves in a confluent mean flow, and the development of disturbances in the summertime synoptic-scale wave train.
The TC energy dispersion has been studied by barotropic models, but has never been documented by direct observations. By using modern satellite products, we reveal for the first time the observed structure of the Rossby wave train associated with the TC energy dispersion. The wave train has an alternating anticyclonic and cyclonic circulation, oriented in a northwest-southeast direction with a typical wavelength of 2000-3000 km. The occurrence of the wave train may depend on the TC intensity and the background mean flow. The cyclogenesis appeared in the cyclonic vorticity region of the Rossby wave train. A scale contraction process is observed associated with the TC formation.
By detecting the propagation signals of the perturbation kinetic energy and precipitation fields, we identified cyclogenesis cases that are associated with the easterly waves. The easterly wave signals may be traced 4-5 days prior to the TC formation, thus providing an excellent precursor for operational genesis forecast several days ahead.
The synoptic-scale wave train is shown to be an important source for the cyclogenesis in the WNP. We found that some of the wave trains were originated from the equatorial Pacific in a form of the mixed Rossby-gravity wave. Others might result from the instability of the summer mean flow.
Thus the satellite data analysis above provides a firm basis for the real-time operational forecast of TC genesis.

H. Simulation of cyclogenesis associated with TC Rossby wave energy dispersion
Motivated by the satellite data analyses of role of the TC energy dispersion, we conducted a numerical investigation to simulate this cyclogenesis process in a state-of-the-art numerical model. The model

used here is the TCM3 model developed by Wang (1999). This model explicitly describes moist dynamics such as cumulus convection and microphysics processes. A major feature is that the model is capable of simulating the fine structure of TC spiral rainband and eye wall. It has been used for the study of maximum potential TC intensity (e.g., Holland 1997), baroclinic TC motion under vertical shear (Wang and Holland 1996), and the dynamics of vortex Rossby waves (Wang 2002). A detailed description of the model and its performance in TC simulations can be found in Wang (1999, 2001). We modify the model by specifying a time-independent basic flow so that we can investigate the cyclogenesis processes under an idealized or realistic background flow. The perturbation part of the governing equations is fully nonlinear. Our objective is to simulate the cyclogenesis associated with the Rossby wave energy dispersion of a preexisting TC. In this experiment, an idealized basic state similar to the observed summer mean state is specified. A mature TC with its well-developed Rossby wave train is specified initially. Two different heating schemes, one with an explicit convective heating scheme and the other with the mass-flux scheme, have been used. In both cases, the TC formation was successfully simulated in the presence of an idealized basic flow similar to the observed summer mean flow in the WNP. A new TC with a minimum central pressure of 970 hPa appears at the wake of a pre-existing TC at day 5.

The dynamic and thermodynamic structures of the simulated new TC bear many similarities to the observed. For instance, the maximum tangential wind appears near the core region of TC at a radius of about 60 km. The low-level wind has a typical wavenumber-one asymmetric structure. A warm core appears in the center of the vortex with the maximum amplitude in the upper troposphere. A spiral rain band rotates around the TC center.

I. Eyewall contraction, breakdown and reformation in a landfalling Typhoon Zeb (Wu, C.-C., K.-H. Chou, H.-J. Cheng, and Y. Wang)

The eyewall evolution is important to intensity change of tropical cyclones (TCs). Dramatic eyewall change can be observed in landfalling tropical cyclones due to the discontinuity of the surface conditions. A typical eyewall evolution in a landfalling typhoon has been documented from both satellite observation and numerical simulation with MM5 in collaboration with C.-C. Wu at the National Taiwan University. The main features of the eyewall evolution of Typhoon Zeb as it interacted with the terrain Luzon is simulated, including the eyewall contraction, breakdown, and reformation during the period when Zeb approached, made landfall at, and left Luzon. In particular, the thermodynamic and kinematic fields at different stages of the eyewall evolution are analyzed. It is shown that the eyewall contraction occurred due to an increased inflow in the coastal region before landfall, which was accompanied by the continual weakening of the storm. The weakening of the storm, the presence of the ambiguous eyewall, and its quasi-breakdown after landfall was likely due to both the terrain dissipation and the latent heat flux cutoff, while the outer circulation was less affected. Finally the outer circulation reorganized and led to the formation of the new large eyewall and its subsequent contraction as Zeb left Luzon. Comprehensive budget analyses are underway to evaluate the interaction among the typhoon eyewall and its larger circulation, the underlying surface and terrain and their effect on storm structure and intensity changes. It is believed that further work can proved a better understanding of the eyewall evolution processes as the TC makes landfall and reach a conceptual model to improve the forecast of severe weather in landfalling TCs (Wu et al. 2003).

J. Assessing the impacts of global warming on tropical cyclone tracks (Liguang Wu and Bin Wang 2003)

K. Effects of air-sea interaction on TC motion (Wu and Wang, in preparation)

How does the air-sea coupling affect the TC motion? Comparison of the track differences between the coupled and uncoupled numerical experiments indicates that the difference is sometimes significant while other times rather moderate, especially for fast-moving tropical cyclones. Why? The response of ocean surface temperature to the surface wind stress is remarkably asymmetric, thus the convective heating is also asymmetric due to oceanic feedback. The asymmetric convective heating affects the TC motion by two processes: generation of asymmetric flows, which may alter advection of symmetric PV, and modification of the PVT tendency, which may deflect the TC toward the maximum PVT area**.** It seems that the track difference depends on how these two processes compete with each other.

IMPACT/APPLICATIONS

This is the first extensive evaluation of the sensitivity of tropical cyclone intensification and intensity to the details of cloud microphysics parameterizations in a tropical cyclone model so far (Wang 2002). In comparison with the substantial sensitivity of simulated tropical cyclones to different cumulus parameterization schemes found in previous studies, the insensivity of the simulated tropical cyclone intensity from this study indicates the potential advantage in using explicit cloud microphysics in tropical cyclone models to improve the intensity forecasting. However, the warm rain-only cloud parameterization should be avoided because it usually produces too much rainfall.

TRANSITIONS

TCM3 has been installed for Prof. C.-C. Wu at the National Taiwan University to support their tropical cyclone research. Prof. Lance Leslie at the University of Oklahoma has recently requested our state-of-the-art cloud microphysics package. This package has also been successfully implemented into our IPRC regional climate model and works quite well. The original cloud microphysics scheme has been updated at BMRC and is continuously being tested in their operational forecast system. Our coupled model has been used by Florida State University (Prof. Zou) to investigate the air-sea coupling process and its impacts on TC intensification.

PUBLICATIONS

The following publications during FY 2003 are supported or partially supported by this grant.

Li, T., B. Fu, X. Ge, B. Wang, and M. Peng, 2003: Satellite data analysis and numerical simulation of tropical cyclone formation. *Geophy. Res. Let. ,* submitted.
Li, T., B. Fu, and F. Weng, 2003: Tropical cyclone formation in the western North Pacific as revealed from the QuikSCAT and TMI data.. *Mon.Wea.Rev.*, submitted.
Wang, Y. 2003: A parameterization for sea surface roughness in high wind regimes based on recent GPS dropsonde data and its effect on tropical cyclone intensity. (Manuscript to be submitted).
Wang, Y., and C.-C. Wu, 2003: Current understanding of tropical cyclone structure and intensity changes–A review. *Meteor. Atmos. Phys*. (submitted).
Wu, C.-C., K.-H. Chou, H.-J. Cheng, and Y. Wang, 2003: Eyewall contraction, breakdown and reformation in a landfalling typhoon. *Geophys. Res. Lett*., **30**, doi:10.1029/2003GL017653.
Wu, Liguang, and B. Wang, 2003: Assessing the impact of global warming on tropical cyclone tracks. Revised, J. Climate.

DISSERTATION AND THESIS

None

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The work done is 100% out-of-house.

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